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Variations in wave conditions in Estonian coastal waters from weekly to decadal scales

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Historical visual observations and numerical hindcasts with the use of the WAM wave model and adjusted geostrophic winds are merged to reveal the basic features of the wave properties and to identify the variations in wave height in different scales in the coastal waters of Estonia. The visually observed wave properties from Vilsandi (1954–2008), Pakri (1954–1985) and Narva-Jõesuu (1954–2008) are compared against wave data hindcast for the entire Baltic Sea for 1970–2007. It is shown that the wave height follows the seasonal variation in wind speed with a maximum in October–January and with a substantial variability on weekly scales. The annual mean wave heights reveal nearly synchronous interannual variations along the entire coast of Estonia until the mid-1980s after which this coherence is lost. The length of the ice season is almost uncorrelated with the annual mean wave heights.

Introduction

The combination of significant wind anisotropy in the Baltic Sea basin, seasonal variation in the wind speed and complicated patterns of long-term changes in wind properties over the entire Scandinavian area (Pryor and Barthelmie 2003, 2010) gives rise to remarkable anisotropy and substantial large spatio-temporal variations in the Baltic Sea wave fields (Jönsson *et al*. 2002, Soomere 2003, Broman *et al*. 2006, Kelpšaitė *et al*. 2008). The information about the wave climate in this area, however, mostly relies on a few measurement sites and on short-term simulations of wave properties with a few years' duration (Soomere 2008). The information is particularly fragmentary for the eastern part of the Baltic Proper. Extremely complex geometry and large variations in wave propagation conditions characterise especially Estonian coastal waters and the Gulf of Finland (Soomere 2005, Laanearu *et al*. 2007, Soomere *et al*. 2008). While a limited amount of wave statistics from the 1990s is available from the central part of the Gulf of Finland for the ice-free time (Pettersson 2001), contemporary instrumental wave measurements are almost missing for the Estonian coastal area. Only recently, data covering five months of wave fields in the nearshore of Saaremaa (Suursaar and Kullas 2009) and one year near the NE coast of Estonia (Suursaar 2010) became available.

The existing data for the coastal areas of the northern Baltic Proper (nBP) reveal several highly interesting features of long-term behaviour of wave properties in this area. A rapid increase in the annual mean wave height in the nBP from the mid-1980s until the mid-1990s and an equally rapid decrease since then were established from both instrumental measurements (Broman *et al*. 2006) and visual observations (Soomere and Zaitseva 2007). While the increase in wave height generally matches similar trends in the North Sea, both the magnitude of the increase and the subsequent decrease in the nBP are somewhat counter-intuitive. Moreover, simple wave models based on one-point wind data did not reproduce these variations (Suursaar and Kullas 2009, Räämet *et al*. 2009). As the recorded changes occurred simultaneously and with a similar relative magnitude at both the eastern and western coasts of the nBP, it is still likely that they expose certain large-scale decadal variations in the wave properties in particular sea areas rather than failures of instruments or the relay of the observers.

An accurate picture of wave properties and their potential changes is necessary for a wide variety of research topics and coastal engineering applications. This problem is particularly important for the Baltic Sea where the impact of waves depends not only on the properties of wave fields but also on external features such as water level or the presence of ice cover. For example, changes in wave climate even in terms of shifts of the stormy season to months with no ice cover may lead to severe destruction of vulnerable beaches of the eastern Baltic Sea (Orviku *et al*. 2003, Ryabchuk *et al*. 2011).

Coarse wave measurements at a few sites along a highly variable coastline frequently do not contain sufficient information about spatial variability of wave fields, particularly in sea areas with complex geometry and nontrivial wind regime such as the Baltic Sea. While the use of visual wave observations has always been problematic because of the lack of reliable data from the open sea areas, nowadays various methods of wave modelling are most widely spread. Although there have been several successful attempts to reproduce local wave properties in the nearshore of Estonia based on one-point wind information and simplified wave models (Soomere 2005, Räämet *et al*. 2009, Suursaar 2010, Suursaar *et al*. 2010), the complexity of geometry and bathymetry of the Baltic Sea combined with extensive variations in the wind properties over the Baltic Sea leads to an acute need for the use of contemporary wave models and realistic wind fields in order to obtain reliable wave statistics. Räämet and Soomere (2010) have demonstrated that the wind wave climatology can be adequately estimated for the Baltic Proper and for the open sea of the Gulf of Finland based on properly adjusted geostrophic wind fields.

In this paper, we make an attempt to merge historical visual observations and numerical hindcasts to reveal seasonal, annual and decadal changes in the basic wave properties in different parts of Estonian coastal waters. As contemporary wave measurements are relatively scarce and short here, we combine different data sources with extensive modelling resources. We first describe the wave model in use and the pool of existing long-term wave observations and instrumental measurements in this area. The basic properties of wave fields such as distributions of the frequency of occurrence of waves of different height and period and short-term (weekly and seasonal) variations in the wave heights are discussed next. Further, long-term variations in the annual mean wave activity are analysed in terms of the mean significant wave height for both original and climatologically corrected data sets, and for 12-month-long time periods containing entire windy autumn and winter seasons.

Methods and data

The analysis below is largely based on visual wave observations at sites operated by the Estonian Meteorological and Hydrological Institute at Vilsandi (1954–2008, Soomere and Zaitseva, 2007), Pakri (1954–1985, Zaitseva-Pärnaste *et al*. 2009) and Narva-Jõesuu (1954–2008, Table 1 and Fig. 1). Features extracted from this data set are compared against instrumental measurements at Almagrundet (1978–2003) on the western coast of the Baltic Proper (Broman *et al*. 2006) and against numerically modelled wave data using the WAM model.

The wave observation routine and technology were identical at all visual observation sites.

As an overview of the routine of observations and a description of the data sets for the sites at Vilsandi and Pakri are given in (Soomere and Zaitseva 2007, Zaitseva-Pärnaste *et al*. 2009), we just present the key features of the routine here. Observations were only made in daylight. The initial observation times (07:00, 13:00 and 19:00 Moscow time, or GMT +3 hours) were shifted to 06:00, 12:00 and 18:00 GMT in 1991. This shift apparently did not cause any substantial inhomogeneity of the time series of the daily mean wave height, which is the property mostly used below.

The observational procedure resembles the classical zero-crossing method. The observer noted the five highest waves during a 5-minute time interval with an accuracy of 0.25 m for wave heights ≤ 1.5 m, 0.5 m for wave heights from 1.5 to 4 m, and 1 m for higher than 4 m waves. Both the height of the highest single wave H_{max} (called maximum wave height below) and the mean height H of these five waves were filed until about 1990. Given the typical wave period of about 2–4 s (*see* below), the estimated mean wave height was actually the average height of top 3%–6% of the waves and thus quite close to the maximum wave height. For the part of data where both the mean and maximum wave heights were filed, the maximum wave height was, on average, only by 6% higher than the mean wave height at Vilsandi (Soomere and

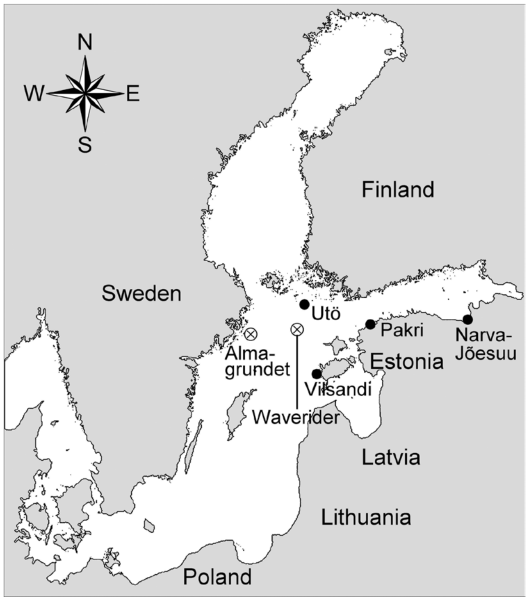

Fig. 1. Location scheme of the long-term wave measurement and observation sites in the Baltic Sea.

Table 1. Basic parameters of wave observations and properties at Vilsandi, Pakri and Narva-Jõesuu. Notice that part of the difference between the average values of the maximum and mean wave heights is connected with the availability of these parameters for different time intervals.

	Vilsandi 1954–2008	Pakri 1954–1985	Narva-Jõesuu 1954–2008
Co-ordinates	58°22´59´´N, 21°48´55´´E	59°23´37´´N, 24°02´40´´E	59°28´06´´N, 28°02´32´´E
Nearest grid point of the wave model WAM	58°24´N, 21°48´E	59°24´N, 24°00´E	59°30´N, 28°00´E
Consistent wave height entries			
total	27131	13283	35027
days covered	15977	9554	15863
Consistent wave period entries			
total	28016	10354	8488
days covered	12553	7724	3514
Largest maximum/mean wave height (m)	8/7.6	6/6	3.4/3.3
Average of the maximum wave heights (m)			
total mean	0.584	0.616	0.455
mean of daily values	0.621	0.610	0.462
Average of the mean wave heights (m)			
total mean	0.511	0.591	0.393
mean of daily values	0.539	0.589	0.391
Mean wave height based on mean of daily values	0.575	0.590	0.391
Number of calm conditions	11417	1923	4692

Zaitseva 2007). In the analysis below, the mean wave height is used; when it was missing, the maximum wave height was used instead. As the potential difference between these quantities is much smaller than the accuracy of the determination of the wave height, doing so did not insignificantly affect the wave statistics.

The wave period (length) was determined as an arithmetic mean from three consecutive observations of the passing time (total length) of 10 waves each time. These waves were not necessarily the highest ones. The experience with visual observations suggests that the observed wave height represents well the significant wave height (historically defined as the mean height of one third of the highest waves) whereas the estimated wave period is only a few tenths of seconds shorter than the peak period (Gulev and Hasse 1998, 1999).

A coastal site reasonably reflecting the nearshore sea state for the predominant strong wind directions (SW and NNW, Soomere and Keevallik 2001) in the nBP is at the Island of Vilsandi (Fig. 1). This site gives inadequate data for easterly winds, which are relatively weak and infrequent in this area. The observed wave properties reasonably well represent also the nearshore sea state conditions at Pakri in the western part of the Gulf of Finland (Fig. 1). Pakri is the only wave observation site on the southern coast of this gulf that is largely open to waves generated in the nBP (Zaitseva-Pärnaste *et al.* 2009). The average depth of the area at Pakri over which the waves were observed was 8–11 m. Unfortunately, wave observations were only performed at Pakri in 1954–1985.

The Narva-Jõesuu meteorological station (59°28´06´´N, 28°02´42´´E, Fig. 1) located on the coast of Narva Bay provides information about wave conditions in the eastern part of the Gulf of Finland. The site from which sea observations were made is located to the west of the station (Table 1). The height of the observation platform (12.8 m above the mean sea level) allows very good observation conditions over the wave observation area located about 200–250 m from the coast where the water depth is 3–4 m. As waves in the Gulf of Finland are generally much lower than in the Baltic Proper, waves do not break in the observation area under most wave conditions. The site is fully open to waves propagating from the NW direction and almost open to waves approaching from the west to the north. Data from Pakri and Narva were considered recently by Zaitseva-Pärnaste *et al.* (2009) as a reference data set allowing some verification of the changes to the wave climate in the Baltic Proper and by Räämet *et al.* (2010) from the viewpoint of potential changes to the wave propagation directions.

For certain comparisons, we use data from Almagrundet (1978–2003, 59°09´N, 19°08´E, Fig. 1; Broman *et al.* 2006), for which the longest instrumentally measured wave data sets in this region are available. Almagrundet is a shoal about 10 nautical miles SE of Sandhamn in the Stockholm archipelago. The fetch for winds from the SW, west, and NW is quite limited at this site. The position of the water surface was sampled over 640 s each hour with upward-looking echo-sounders. Single waves were identified using the zero-downcrossing method. An estimate of the significant wave height H_S was found from the 10th highest waves in a record under the assumption that wave heights are Rayleigh distributed. The water at the location of the instruments was deep enough (about 30 m) for most of the wave fields to follow the Rayleigh distribution of wave heights. The data from 1978–1995 reliably describes the wave properties in this region. Another data set from 1993–2003 have certain quality problems: the overall behaviour of the wave height is adequate but the periods are not usable (Broman *et al.* 2006).

All the listed sites are coastal and thus only conditionally represent open sea conditions. The sites are fully open to a range of predominant wind directions. The waves in the Baltic Sea are relatively short and thus less affected by the finite-depth effects compared to much longer ocean waves at a similar depth. The sheltering effect of the shoreline and the relatively low water depth at the observation sites still may at times significantly alter local wave properties compared to those in the open sea due to the shoaling, refraction and damping of the waves.

The most representative wave data for the nBP stem from a directional waverider operated by the Finnish Institute of Marine Research (FIMR) (from 2008 by the Finnish Meteorological Institute) in the nBP at a depth of about 100 m (Fig. 1, 59°15´N, 21°00´E) since September 1996 during the ice-free seasons (Kahma *et al*. 2003). Although this time series is not long enough for determining long-term variations in wave properties, we use this data as a reference set for comparisons with wave statistics at different sites.

The properties of wave fields at all three visual observation sites were also hindcast for the years 1970–2007 with the use of the third-generation spectral wave model WAM (Komen *et al*. 1994). The basic model setup follows the one described in (Soomere 2003). The presence of ice was ignored. The calculation was done for a regular rectangular grid with a resolution of about 3 × 3 nautical miles (11545 sea points) covering the entire Baltic Sea. At each sea point, 1008 components of the two-dimensional wave spectrum (24 evenly spaced directions, 42 frequencies starting from 0.042 Hz with an increment of 1.1) were computed. Differently from the standard configuration of the WAM model (that does not account for waves with periods < 2 s), an extended frequency range up to about 2 Hz (wave periods down to 0.5 s) was used to ensure realistic wave growth rates in low wind conditions after calm situations (Soomere 2005).

The WAM model was forced with a wind field derived from geostrophic winds provided by the Swedish Meteorological and Hydrological Institute (SMHI). In order to construct the near-surface wind at 10 m level, used as the input wind to the model, the geostrophic wind speed was multiplied by 0.6 and the direction turned by 15° to the left (cf. Bumke and Hasse 1989) as in many contemporary studies into the Baltic Sea dynamics (Myrberg *et al*. 2010). The wind time step was 6 hours before September 1977 and 3 hours since then.

Owing to the finite resolution of the wave model, there is always a certain difference between the location of an observation or measurement site and the nearest grid point for which the wave properties are calculated. The performance of the model, the match of the basic statistics of numerically simulated wave conditions with those observed at different sites and shortages connected with the use of different wind forcing are discussed in (Räämet and Soomere 2010). Several examples of the comparison of the time series and wave statistics of measured and observed data with the results of numerical simulations based on the WAM model and a simpler fetch-based model are provided by Räämet *et al*. (2009). The model performance was somewhat better for the Almagrundet area when the MESAN wind data (Häggmark *et al*. 2000) were used but for the open Baltic Sea the use of geostrophic winds showed a better match with the measurements.

The analysis below involves wave heights specified in three different manners: visually observed wave heights, the significant wave height calculated by using Rayleigh statistics at Almagrundet and the significant wave height estimated from the two-dimensional energy spectrum in the WAM model. The potential differences between these quantities, for example, because of a violation of the Rayleigh distribution in the nearshore, suggest that the instantaneous values and the average characteristics found from different sources may differ to some extent. On the other hand, the use of a particular method for obtaining an estimate for the wave height apparently does not distort the basic features of spatio-temporal variations in the wave fields such as their typical time scales and the direction and relative magnitudes of the trends.

Basic properties and seasonal variations of wave fields

The digitized data sets were first checked for consistency (e.g. whether large wave heights were associated with relative large periods). Joint distributions of wave heights and periods for the three observation sites are discussed by Räämet *et al*. (2010). A few (about 50) recorded wave heights > 4 m were interpreted as erroneous at Vilsandi where the water depth in the observation area is about 4 m (Soomere and Zaitseva 2007). Much higher waves, however, may occur at Pakri where the data set contains six cases when a maximum wave height was ≥ 5 m. These cases evidently correspond to realistic wave conditions in rough seas. The highest waves (6 m) were recorded on 6–7 August 1967 when a strong NW storm caused extensive

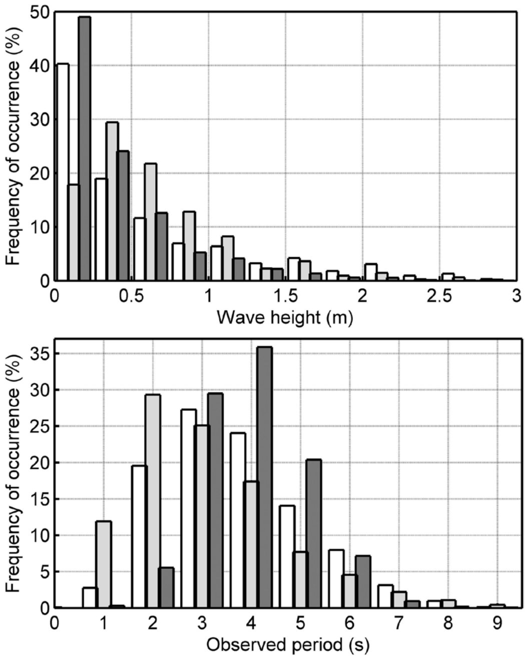

Fig. 2. Frequency of occurrence of different wave heights (above, resolution 0.25 m) and mean periods (below, resolution 1 s) at Vilsandi (white bars), Pakri (light grey bars) and Narva-Jõesuu (dark grey bars).

damage to the forests in Estonia. Waves with a height of 5 m were recorded on 21 January 1964 and on 23 September 1969.

As expected, the maximum wave heights were much lower at Narva-Jõesuu where they exceeded 3 m only four times. The largest maximum/mean wave heights (3.4/3.3 m) were recorded on 25 October 1957 and twice on 28 August 1961. Also on 15 October 1954 the maximum wave height over 3 m (maximum/mean 3.1/2.9 m) was observed.

The distributions of the occurrence of different wave heights at Vilsandi, Pakri and Narva-Jõesuu (Fig. 2) reflect all consistent observations of wave heights with non-zero wave periods. As there were systematically more observations per day in fairly calm spring and summer seasons, these distributions slightly overestimate the proportion of relatively low wave conditions. The distributions of wave periods are similarly biased. Notice that they reflect older observations as the periods were only recorded until the mid-1990s (Soomere and Zaitseva 2007: table 1).

The distributions in question reveal very high frequency of low waves with heights below 0.25 m at Vilsandi and Narva-Jõesuu (Fig. 2) and resemble analogous distributions for semi-sheltered bays of the Gulf of Finland (Soomere 2005). They are largely different from the analogous distributions for Almagrundet (Broman *et al*. 2006), for the nBP (Soomere 2008) and even for Pakri. Differently from Vilsandi and Narva-Jõesuu, the relevant distributions at Pakri, nBP and Almagrundet match the Rayleigh distribution well.

Although the Pakri observation site is sheltered from a part of the predominant SW winds, the distribution of wave periods at this site matches the distribution for the nBP (Kahma *et al*. 2003). The most frequent wave periods are 2–3 s. Interestingly, wave periods observed at Narva-Jõesuu are somewhat longer than those at Vilsandi and Pakri: the most frequent periods are 3–5 s as in the open part of the nBP (Kahma *et al*. 2003). This feature may be explained by a specific feature of wave generation and propagation in the Gulf of Finland. Namely, relatively long waves travelling along the axis of the gulf are frequently excited in this water body even when the wind blows obliquely with respect to this axis (so-called slanted fetch conditions, Pettersson 2004, Pettersson *et al*. 2010).

In order to remove the bias caused by the larger number of observations per day during the relatively calm spring and summer seasons, the entire analysis below is based on the set of daily mean wave heights (Soomere and Zaitseva 2007, Zaitseva-Pärnaste *et al*. 2009). The average wave height, calculated from daily mean wave heights, is 0.511 m at Vilsandi, 0.591 m at Pakri, and 0.393 m at Narva-Jõesuu (Table 1). This is clearly smaller than the mean significant wave height at Almagrundet (0.876 m in 1978–1995 and 1.04 m in 1993–2003, Broman *et al*. 2006). The wave height medians are 0.3 m, 0.5 m and 0.35 m for Vilsandi, Pakri and Narva-Jõesuu, respectively; these are also much smaller than at Almagrundet. Notice that the presented mean values in some cases reflect different time intervals and thus are not always directly comparable.

In general, all the data sets, albeit to some extent affected by the presence of the coast, reproduce the basic features of the northern Baltic Sea wave fields (Soomere 2008) such as

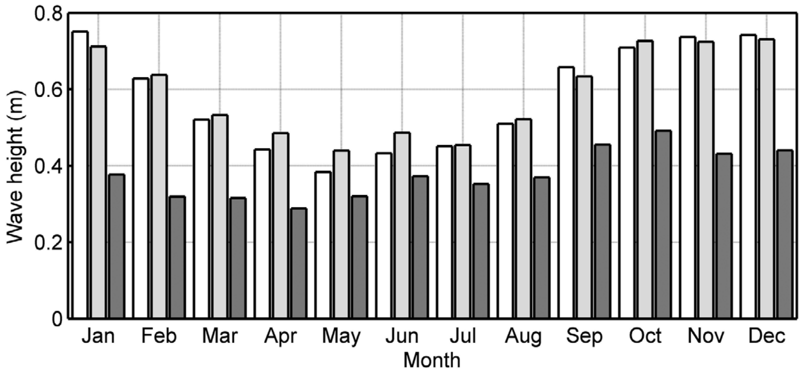

Fig. 3. Seasonal variation in the monthly mean wave height at Vilsandi (white), Pakri (grey) and Narva-Jõesuu (dark grey).

(i) the overall mild wave regime in the basin, with the overall mean wave height in the open sea approximately 1 m, in the coastal areas 0.5–0.6 m (Suursaar and Kullas 2009) and in semi-sheltered bays about 0.3–0.4 m (Soomere 2005); (ii) a large proportion of wave conditions with the significant wave heights around 0.5 m (Fig. 2), and (iii) the most frequent peak periods 4–6 s in the open sea and 2–4 s in the nearshore regions (Fig. 2). The listed values are characteristic of relatively small basins and are considerably smaller than the respective values for the open ocean.

The seasonal course of the wave heights at the observation sites is discussed by Räämet and Soomere (2010) and we present here only its main features. The wave conditions exhibit a strong seasonal variability at all sites (Fig. 3), which is the most pronounced at Vilsandi where the monthly mean wave height varies from about 0.38 m during summer to about 0.75 m in winter. The highest wave activity occurs in January and almost as high waves are observed from October to December. The calmest months are the spring and summer months from March to August, with a well-defined minimum in April or May. Such an annual variation mostly matches the annual variation of the wind speed in the nBP (Mietus 1998, Räämet and Soomere 2010). It also resembles the cycle of water level in adjacent coastal waters of Finland (Johansson *et al*. 2001).

The seasonal variation in the wave heights is much more pronounced at Almagrundet where the mean wave heights in the roughest and in the calmest months differ 2.2–2.6 times (Broman *et al*. 2006). This difference most probably stems from the impact of the coast upon visually observed wave conditions (Soomere and Zaitseva 2007). Almagrundet is located far enough from the coast to capture to some extent the properties of waves created by winds blowing offshore from the mainland while at the coastal sites the observer usually files calm seas under such conditions (cf. Table 1).

Although Pakri is sheltered from some of the waves excited by the most frequent (SW) winds, the overall mean wave height at Pakri and its seasonal variation almost exactly coincide with those at Vilsandi. Interestingly, the long-term observed and simulated wave heights also almost exactly coincide at this site (Räämet and Soomere 2010). This feature suggests that Pakri wave data to a large extent capture the wave conditions in the open sea but also indicates that the simulations in (Räämet and Soomere 2010) apparently underestimate the wave heights in the open sea.

There is a less pronounced but still clearly identifiable annual cycle in wave activity at Narva-Jõesuu (Fig. 3). The calmest months at this site are, as mentioned above, April and May. Differently from other sites, the roughest months in Narva Bay are September and October, when the monthly mean wave height exceeds 0.4 m. Relatively low values of the monthly mean wave heights at this site in November–December compared with those in October apparently reflect the frequent presence of sea ice on the coasts of Narva Bay and in the entire eastern Gulf of Finland in late autumn (Sooäär and Jaagus 2007).

There are some interesting variations in wave intensity within certain months. They become evident through the analysis of the climatological mean wave heights for single days (Fig. 4).

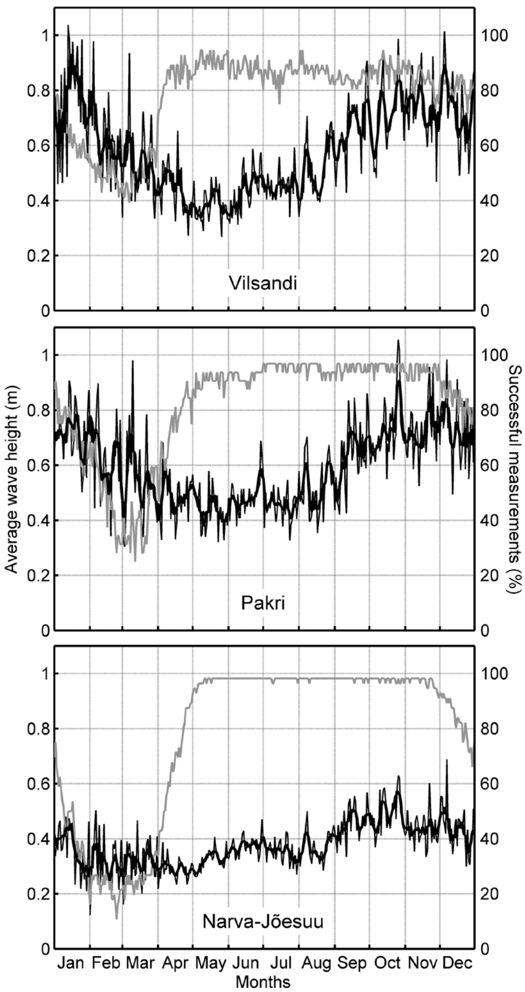

Fig. 4. Climatological mean wave heights at Vilsandi, Pakri and Narva-Jõesuu over all available wave observations (solid lines), their 5-day running averages (black) and the percentages of days with at least one successful observation on a given calendar day (grey). Data from 29 February are merged with data from 1 March.

This value is calculated for each calendar day over 55 years at Vilsandi and Narva-Jõesuu and over 31 years at Pakri. It eventually contains some noise, the level of which is the largest for the season when a relatively small number of measurements exist. Surprisingly, several short-time variations are synchronous at all three sites. This feature once more confirms that the results of visual observations give an adequate picture of wave statistics although single measurements may contain quite a large error.

The largest short-time feature in the wave activity is the relatively calm period at all sites at the end of December and the beginning of January. It can be clearly recognised from Vilsandi and Pakri data, and is somewhat less pronounced at Narva-Jõesuu. Short time periods with noticeably higher waves occur in all records during the first week of August, in the middle of September, at the end of October and at the beginning of December.

Long-term variations in wave heights

Long-term variations in wave conditions will be discussed below based on three sets of time series derived from wave observations, data from Almagrundet and numerically simulated time series. The analysis of the annual mean wave heights (called (overall) wave intensity below) obtained directly from the uncorrected daily mean values of observed wave conditions during a calendar year (Fig. 5) is complemented with analogous time series in which the missing measurements have been replaced by their climatological values for the same calendar day.

The reason behind the relatively large values of the annual mean wave height at Vilsandi in 1954–1956 is unclear. As the number of storm days was unusually large on the western coast of the Baltic Proper in these years (Bergström *et al*. 2001), such high wave intensity at Vilsandi may be real. Still we omit these years in the correlation analysis below.

All four time series of the annual mean wave heights based on visual observations and instrumental measurements in a calendar year show a reasonable match of years of relatively high and low wave intensity at all measurement sites in 1957–1986 (Fig. 5 and Table 2). Accordingly, there is a high correlation between annual mean wave heights at all sites in 1957–1986, with the correlation coefficients ranging from 0.44 to 0.53. The corresponding p-values are of the order of 0.01 or even smaller, indicating statistically significant correlation at 99% or higher level. The short-term interannual variability with time scales of 1–3 years had, therefore, the same appearance along the entire section of the Baltic

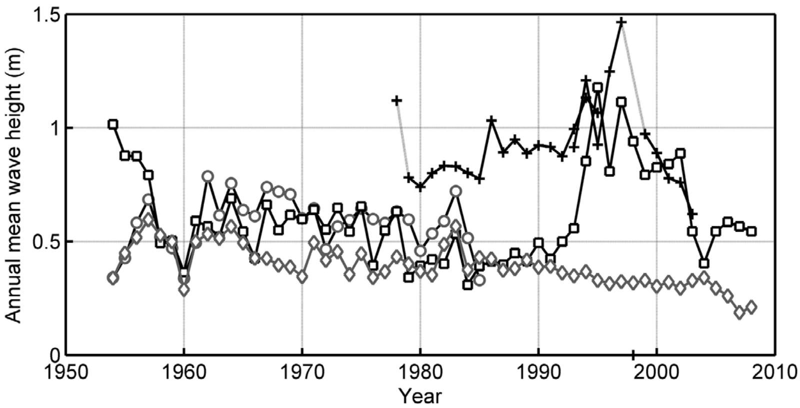

Fig. 5. Long-term variations in the annual mean wave height at Vilsandi (circles), Pakri (squares), Narva-Jõesuu (diamonds) and Almagrundet (crosses).

Sea coast from the Baltic Proper to Narva Bay in these years.

Interestingly, this coherence in the long-term variation in wave heights disappears abruptly at the end of the 1980s (Fig. 5 and Table 2). While the wave activity reveals a drastic decadal-scale increase and decrease in the Baltic Proper during the latter two decades, a gradual decrease in the annual mean wave height (0.4% per annum) is observed at Narva-Jõesuu. Differently from the period before the 1980s, years with relatively high wave intensity at Vilsandi correspond to relatively calm years in Narva Bay and *vice versa*.

This change is vividly expressed in terms of correlations between the observed and simulated annual mean wave heights (Table 2). It can seen in Fig. 5 that the coherence is abruptly lost starting from the year 1987; for this reason we compare below the course of wave heights in 1954–1986 and from 1987 onwards. The correlation between the time series for Vilsandi and Narva-Jõesuu is negative for 1987–2008 and the p value suggests that there is no correlation indeed.

A similar loss of correlation also occurs for the observed and numerically simulated time series of the annual mean wave heights. The correlation is statistically significant until about the year 1987 for all three sites but is much weaker (for Narva-Jõesuu) or virtually lost (for Vilsandi) since then (Table 3). This feature becomes even clearer in comparing simulated data with observed time series in which the missing observations are replaced by climatological mean values for the given calendar day (*see* below).

The described features indicate that certain substantial changes in wind properties apparently have occurred over the Baltic Sea since the mid-1980s. These changes, if real, have become evident as an increase in the wave intensity in areas open to southerly winds. They, however, have resulted in almost no changes in regions affected by waves approaching from the northern and western directions (cf. Kelpšaitė *et al*. 2009). Further, the described changes have occurred on the background of gradually increasing wind speeds in the Baltic Proper (Pryor and Barthelmie 2003, 2010, Broman *et al*. 2006). Consequently, such changes have mostly affected southern and SW winds.

This conjecture matches the results of the analysis by Kull (2005), who demonstrated that important changes to the directional structure

Table 2. Correlation coefficients between the annual mean wave heights at Vilsandi, Pakri and Narva-Jõesuu. The upper right cells show correlations for 1957–2008 (also separately for 1957–1986/1987–2008 for Vilsandi and Narva-Jõesuu); the lower left cells show the relevant p values.

Site	Vilsandi	Pakri	Narva-Jõesuu
Vilsandi	–	0.53	–0.14 (0.49/–0.25)
Pakri	$p = 0.0023$	–	0.44
Narva-Jõesuu	$p = 0.28$ (0.0028/0.47)	$p = 0.014$	–

of winds and wind properties have occurred over Estonia. Namely, during the last 40 years there has been a significant increase in the frequency of SW winds and a decrease in southern and eastern winds all over Estonia. Such a change may be responsible for a large part of the increase in wave activity in the nBP as it leads to a systematic increase in the typical fetch length in this basin. On the other hand, this change also explains well why the annual mean wave heights have been almost constant or even decreased in Narva Bay.

Variations in climatologically corrected wave heights

It is important to verify the adequacy of the observed wave data (especially from Vilsandi, which show drastic variations in wave heights in the late 1990s and at the turn of the millennium) against major sources of potential errors or biases in observations such as large gaps in the time series or substantial changes in the duration of ice cover in the vicinity of the observation site. There are large gaps in the observations from Vilsandi in 1991–2004 (Soomere and Zaitseva 2007). For example, there are no data for July–September 1990 and no wave observations were performed in August–December 1997. Also, there has been a steep decrease in the average number of days with ice in the entire Western Estonian Archipelago (Jaagus 2006). As the annual mean wave heights were calculated based on the average wave heights only over the days when at least one consistent wave observation was performed, the missing of data from relatively calm periods eventually lead to an overestimation of the annual mean wave height. Similarly, the missing of wave data from a windy season generally leads to an underestimation of the annual mean wave activity.

While the impact of the missing of data from summer seasons on the annual mean wave height is intuitively obvious, the impact of the gradual lengthening of the ice-free season may be more complicated. The ice cover on the coasts of the western Estonian Archipelago occurred from mid-November to mid-April in the past. The changes in the beginning and end of the ice season have been almost symmetric during the last century, with a slightly larger number of additional ice-free days in spring (Jaagus 2006). As December (which is mostly ice-free nowadays) is one of the windiest months and April (which is also largely ice-free now at Vilsandi) is one of the calmest months, this pattern of changes is not expected to lead to any large change in the annual average wave height. (This conjecture does not hold in terms of the total wave load on the coasts, which obviously increases with an increase of the length of the ice-free season.) Therefore, the correlation between the annual mean wave intensity and the

Table 3. Correlation coefficients, bias and standard deviation (SD) between numerically simulated and observed time series of the annual mean wave height at Vilsandi, Pakri and Narva-Jõesuu for the calendar years. The division of the data set into two sub-intervals is made so that the contrast in the relevant correlation coefficients is maximised.

	Uncorrected data			Climatologically corrected data		
	Correlation (*r*)	Bias (cm)	SD (cm)	Correlation (*r*)	Bias (cm)	SD (cm)
Vilsandi						
1970–2007	0.13	2.8	21.3	0.32	13.4	16.3
1970–1988	0.34	6.5	12.5	0.53	10.5	12.0
1988–2007	0.16	11.0	27.2	0.06	16.0	19.7
Pakri						
1970–1984	0.64	1.3	5.3	0.64	1.6	4.8
Narva-Jõesuu						
1970–2007	0.36	9.7	11.8	0.32	8.8	10.3
1970–1985	0.74	4.5	6.1	0.69	5.8	6.9
1985–2007	0.15	12.9	14.4	0.03	10.6	12.1

length of the ice season is mostly implicit and may simply reveal unfavourable conditions for ice formation either through an increased winter temperature or by the frequent presence of relatively high waves.

In order to eliminate part of potential distortions caused by the lack of data, we amended the recorded time series of wave heights with the use of the climatological mean values of the wave heights for each calendar day. Doing such a "climatological correction" introduces a certain amount of noise because of the character of seasonal variations of the daily mean wave height (Fig. 4). Compared with the option of replacing missing observations by the relevant climatological monthly mean values, the described method avoids a bias connected with gaps in data for the transitional months such as April and with above-discussed variations in the wave heights in weekly scales. Physically, introducing such a correction is equivalent to largely ignoring the ice cover. Consequently, the results should have a better match with the numerically simulated ones.

There is a clear divergence between the annual mean wave heights obtained from the observed time series and from the climatologically corrected time series at Vilsandi in 1970–1990 (Fig. 6). The climatologically corrected values differ by up to 30% from the relevant values based on original data. As expected, the corrected mean wave heights are larger for years with relatively low wave intensity and long ice cover (for example, in the 1970s). The corrected mean wave heights are by up to 20% smaller in the 1990s and at the turn of the millennium. As expected, the wave intensity in climatologically corrected time series is clearly smaller than according to the original data for extremely stormy years 1995 and 1997 (Fig. 6). The increase in the overall wave intensity at the beginning of the 1990s is smoother but still substantial in 1993–2002. The best estimate for the actual wave intensity apparently lies between the two values.

The two estimates for the annual mean wave heights differ much less for Pakri and Narva-Jõesuu (except for a few most recent years, Fig. 6). The largest difference becomes evident for Narva-Jõesuu starting from 2005. Interestingly, the original and corrected values almost exactly coincide for Vilsandi for these years.

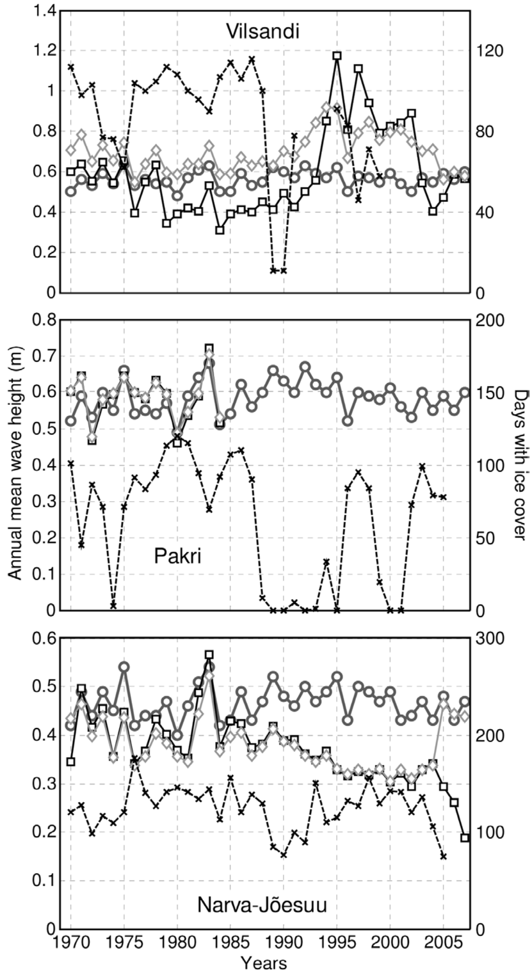

Fig. 6. Long-term variations in wave and ice conditions calculated based on calendar years at Vilsandi (upper panel), Pakri (middle panel) and Narva-Jõesuu (lower panel): original observed time series (squares), climatologically corrected time series (diamonds), numerically simulated time series (circles) and the length of ice season (crosses, estimated as the number of days from the first appearance of ice to the total disappearance of ice).

The climatological correction leads to a substantial increase in the correlation between simulated and observed annual mean wave heights (Table 3), in particular, for years of coherent observed and simulated interannual changes. This feature is not unexpected, because the presence of ice is ignored in simulations. On the contrary, the correlation between the simulated and observed values of the annual mean wave heights is completely lost for the years 1988–2007.

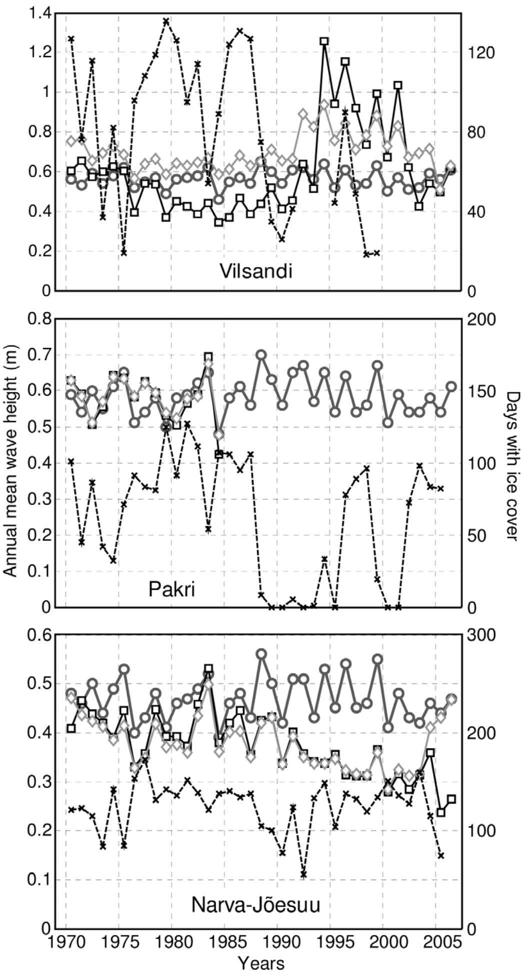

Fig. 7. Long-term variations in wave height over windy seasons (1 July–30 June of the subsequent year) at Vilsandi (upper panel), Pakri (middle panel) and at Narva-Jõesuu (lower panel). Notations are the same as for Fig. 6.

Filling the gaps with climatological values leads to a substantial increase in the difference of estimates of the long-term average wave intensity at Vilsandi. While for the original data the bias between the model results and observations was 2.8 cm, it increases to 13.4 cm for the amended data (Table 3). The increase in the difference is the largest for the years 1988–2007 for which the match of the observed and modelled data was the worst. The resulting bias is close to that obtained in the comparison of the measured and modelled data for Almagrundet (Räämet *et al*. 2009). This feature could be interpreted as additional evidence that the wind forcing in use in the wave hindcast leads to an overall slight underestimation of wave heights in the Baltic Proper.

Stormy and ice seasons

The time series of the annual mean wave heights presented above were calculated over two relatively windy time periods each year (January–February and September–December). As stormy seasons and periods with ice cover may occur during quite different months in different years (Sooäär and Jaagus 2007), comparisons based on calendar years may give somewhat distorted reflection of the severity of wave conditions in a particular autumn–winter windy season. A time series that more adequately reflects the overall wave conditions during different stormy seasons is that of the average wave height over periods covering the entire windy season (September–March), separated by a date corresponding to one of the lowest annual wave heights. For simplicity, below we consider the average wave height over periods 01 July to 30 June of the subsequent year calculated, as above, from the daily average observed wave heights.

The basic properties of long-term variations in the wave intensity at all the sites are the same as revealed by the time series over calendar years (Fig. 7). There is high interannual variation around the year 1960 in all the data sets, a period of relatively low wave intensity in the 1980s and a drastic increase in wave heights over the 1990s at Vilsandi.

The correlations between simulated and observed data are almost the same (albeit slightly lower) as for the data over calendar years for Pakri and Vilsandi (Tables 3 and 4). The similar correlations for Vilsandi are almost the same for the last two decades but considerably higher for the originally observed and simulated data for the entire period of simulations 1970–2007 and for climatologically corrected data for 1988/1989–2006/2007. This feature suggests that periods containing long-lasting rough seas are concentrated at Vilsandi in a few months whereas such periods may happen either in autumn or in winter. The WAM model and the forcing in use represent such periods. The analysis over calendar years apparently has a tendency to smooth out their contribution into the annual mean wave height by means of splitting them between subsequent calendar years. Interestingly, the simulated and observed wave heights move in antiphase for 1972/1973 at Pakri whereas all other changes are mostly in phase in other years both at Pakri and Narva-Jõesuu (Fig. 7).

One of the key features forming the wave fields is ice cover. The maximum area covered by ice in the Baltic Sea substantially varies between years (Bergström *et al*. 2001, Leppäranta and Myrberg 2009). For example, at Vilsandi the duration of ice cover may vary from a few to > 100 days during a winter (Fig. 6). The presence of ice may have a twofold impact on the observed wave data. First, fast ice makes wave observations impossible, leading to gaps in the time series. Second, an ice cover upwind from the observation site reduces the effective fetch length and thus the observed wave height and period. As the open part of the Baltic Proper does not freeze during "normal" winters, this effect is not likely to affect the predominant waves that approach Vilsandi from the ice-free SW direction. It may, however, damp the generation of waves during N-NW storms at all sites in question.

Typically, Estonian coastal waters are ice-covered from January to March (Sooäär and Jaagus 2007). The above analysis (Fig. 3) suggests that the absence of ice cover in January would generally lead to an increase in the annual mean wave height at Vilsandi and Pakri, but the absence of ice cover in February and especially in March–April would lead to its decrease. Comparison of the interannual variations in the mean wave height calculated from observations and from climatologically corrected data (Figs. 6 and 7) confirms this pattern of changes. The artificial "lengthening" of the ice-free period by inserting climatological values for the missing measurements leads to a clear increase in the annual mean wave height at Vilsandi in normal and relatively severe winters of 1975–1988.

In areas where the season of the potentially highest waves overlaps with the ice season (such as the eastern part of the Gulf of Finland where fast ice is frequently formed in November) the reduction of the ice season may lead to a drastic intensification of coastal processes (Ryabchuk *et al*. 2011). This process may be intensified to some extent by the presence of longer fetch in coastal areas of the NE Baltic Proper.

There is almost no difference between the annual mean wave heights calculated from the original and climatologically corrected data for Pakri and Narva-Jõesuu. Consequently, these areas are relatively calm in mild winters. This feature is not fully unexpected, because the more frequent presence of mild winters apparently occurs simultaneously with an increase in the frequency of SW winds (Kull 2005). Such winds generally excite large waves neither at Pakri nor at Narva-Jõesuu.

Table 4. Correlation coefficients, bias and standard deviation (SD) between numerically simulated and observed time series of the mean wave height at Vilsandi, Pakri and Narva-Jõesuu calculated for the time periods from 1 July to 30 June of the subsequent year. The separation into sub-intervals is the same as for Table 3.

	Uncorrected data			Climatologically corrected data		
	Correlation (*r*)	Bias (cm)	SD (cm)	Correlation (*r*)	Bias (cm)	SD (cm)
Vilsandi						
1970/1971–2006/2007	0.28	3.4	22.2	0.38	13.5	16.2
1970/1971–1988/1989	0.28	7.6	12.5	0.35	9.6	11.3
1988/1989–2006/2007	0.17	13.0	29.3	0.29	16.7	20.0
Pakri						
1970/1971–1984/1985	0.58	0.5	5.4	0.57	1.0	4.7
Narva-Jõesuu						
1970/1971–2006/2007	0.38	9.6	11.5	0.36	9.0	10.6
1970/1971–1985/1986	0.66	4.8	6.0	0.65	6.0	7.1
1985/1986–2006/2007	0.43	12.6	14.2	0.29	11.0	12.6

Finally, the analysed data show virtually no correlation between the annual mean wave height (optionally calculated over different time periods and/or with the use of climatologically corrected values) and the length of ice cover at the sites (Figs. 6 and 7). Although there is some qualitative match of these quantities in single years, the relevant correlation coefficient is well below 0.2 and no statistically significant correlation exists.

Discussion and conclusions

The data sets of visual wave observations from Estonian coastal sites Vilsandi, Pakri and Narva-Jõesuu cannot be used as an adequate approximation of the time series of the sea state because of their low temporal resolution. Yet the performed analysis suggests that the data represent well the general features of the wave fields in the northern Baltic Sea (Jönsson *et al*. 2002, Soomere 2008) such as a relatively low overall wave activity, short wave periods, and substantial seasonal and interannual variation of the wave conditions. The basic properties of the distributions of wave heights and periods and the overall mean and typical wave parameters largely follow the heuristically understandable patterns governed by the combination of the predominant strong winds and the geometry of the Baltic Sea. Especially Pakri data seem to reflect the open sea wave properties adequately.

Our analysis also revealed several intriguing features of wave fields in different coastal sections of the NE Baltic Proper and the Gulf of Finland. The most interesting outcome is a substantial change in the match of the long-term course in the wave activity in different coastal sections. The annual mean wave height showed nearly synchronous, substantial decadal-scale variations over the entire coastline of Estonia from the 1960s until the mid-1980s. Starting from the end of the 1980s, this coherence is lost and the temporal course of wave activity has been essentially decoupled in the northern Baltic Proper and the Gulf of Finland.

A minor feature, the nature and reliability of which are unclear, is that wave storms seem to be unevenly distributed in single months and there is an almost two weeks long relatively calm period around Christmas and the New Year.

Our analysis supports the impression that there has been a clear increase in the overall wave intensity in the northern Baltic Proper over the 1990s (Broman *et al*. 2006, Soomere and Zaitseva 2007). The increase in the annual mean wave height has been substantial, from about 0.5 m to the level of > 0.8 m, with a subsequent decrease to the level of the 1980s in 2005–2008. This pattern of changes is supported by the match of the data from Almagrundet and Vilsandi. It is somewhat surprising that simulations with the use of the high-resolution WAM model forced by adjusted geostrophic winds do not reveal these extensive variations although they do capture the short-term interannual variability of wave heights at Vilsandi, in particular, for the values calculated for the autumn-winter seasons. This feature deserves future detailed studies.

Another surprise was that no trend of increasing wave activity could be identified either in the northern Baltic Proper or at the entrance to the Gulf of Finland although the mean wind speed continues to increase over the area (Pryor and Barthelmie 2003, 2010, Broman *et al*. 2006). Moreover, the wave climate in the SE part of the Gulf of Finland is even characterized by a gradual decrease (0.4% per annum) in the wave height.

It is debatable what causes such mismatches and the loss of spatial coherence of the changes in the wave properties over the area studied. The changes in the ice conditions may have affected the course of wave activity at Vilsandi to some extent but evidently have no substantial influence on what was observed at Narva-Jõesuu as there have been virtually no changes in the beginning of the ice season (Sooäär and Jaagus 2007). A viable explanation is the radical change in the directional structure of moderate and strong winds – a substantial increase in the frequency of SW winds (Kull 2005, Jaagus 2009), which are able to excite high waves at both the eastern and western coasts of the northern Baltic Proper. Such changes affect only a limited part of the Baltic Proper and are consistent with analysis in (Kelpšaitė *et al*. 2008, 2009) that identified no substantial changes in wave heights in its southern sections and on the southern coast of the Gulf of Finland. The reasons behind the described patterns of changes evidently are not local and may be related to the shifts of the trajectories of cyclones (Alexandersson *et al*. 1998, Suursaar *et al*. 2006) or to certain changes in other parameters of the large-scale circulation.

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References

Alexandersson H., Schmith T., Iden K. & Tuomenvirta H. 1998. Long-term variations of the storm climate over NW Europe. *Global Atm. Ocean System* 6: 97–120.

Bergström S., Alexandersson H., Carlsson B., Josefsson W., Karlsson K.-G. & Westring G. 2001. Climate and hydrology of the Baltic Basin. In: Wulff F., Rahm L. & Larsson P. (eds.), *A systems analysis of the Baltic Sea*, Ecological Studies vol. 148, Springer, Berlin, Heidelberg, pp. 75–112.

Broman B., Hammarklint T., Rannat K., Soomere T. & Valdmann A. 2006. Trends and extremes of wave fields in the north–eastern part of the Baltic Proper. *Oceanologia* 48: 165–184.

Bumke K. & Hasse L. 1989. An analysis scheme for determination of true surface winds at sea from ship synoptic wind and pressure observations. *Bound. Lay. Meteor.* 47: 295–308.

Gulev S.K. & Hasse L. 1998. North Atlantic wind waves and wind stress fields from voluntary observing ship data. *J. Phys. Oceanogr*. 28: 1107–1130.

Gulev S.K. & Hasse L. 1999. Changes of wind waves in the North Atlantic over the last 30 years. *Int. J. Climatol*. 19: 1091–1117.

Häggmark L., Ivarsson K.-I., Gollvik S. & Olofsson P.-O. 2000. MESAN, an operational mesoscale analysis system. *Tellus* 52A: 2–20.

Jaagus J. 2006. Trends in sea ice conditions in the Baltic Sea near the Estonian coast during the period 1949/1950–2003/2004 and their relationships to large-scale atmospheric circulation. *Boreal Env. Res*. 11: 169–183.

Jaagus J. 2009. Pikaajalised muutused tuule suundade korduvuses Eesti läänerannikul. *Tallinna Ülikooli Ökoloogia Instituut. Publikatsioonid* 11: 11–24.

Johansson M., Boman H., Kahma K.K. & Launiainen J. 2001. Trends in sea level variability in the Baltic Sea. *Boreal Env. Res*. 6: 159–179.

Jönsson A., Broman B. & Rahm L. 2002. Variations in the Baltic Sea wave fields. *Ocean Eng*. 30: 107–126.

Kahma K., Pettersson H. & Tuomi L. 2003. Scatter diagram wave statistics from the northern Baltic Sea. *MERI — Report Series of the Finnish Institute of Marine Research* 49: 15–32.

Kelpšaitė L., Herrmann H. & Soomere T. 2008. Wave regime differences along the eastern coast of the Baltic Proper. *Proc. Estonian Acad. Sci*. 57: 225–231.

Kelpšaitė L., Parnell K.E. & Soomere T. 2009. Energy pollution: the relative influence of wind-wave and vessel-wake energy in Tallinn Bay, the Baltic Sea. *J. Coastal Res*. Special Issue 56: 812–816.

Komen G.J., Cavaleri L., Donelan M., Hasselmann K., Hasselmann S. & Janssen P.A.E.M. 1994. *Dynamics and modelling of ocean waves*. Cambridge University Press, Cambridge.

Kull A. 2005. Relationship between interannual variation of wind direction and wind speed. *Publicationes Instituti Geographici Universitatis Tartuensis* 97: 62–73.

Laanearu J., Koppel T., Soomere T. & Davies P.A. 2007. Joint influence of river stream, water level and wind waves on the height of sand bar in a river mouth. *Nordic Hydrol*. 38: 287–302.

Leppäranta M. & Myrberg K. 2009. *Physical oceanography of the Baltic Sea*. Springer Praxis, Berlin, Heidelberg, New York.

Mietus M. (co-ordinator) 1998. *The climate of the Baltic Sea Basin. Marine meteorology and related oceanographic activities*. Report 41, World Meteorological Organisation, Geneva.

Myrberg K., Ryabchenko V., Isaev A., Vankevich R., Andrejev O., Bendtsen J., Erichsen A., Funkquist L., Inkala A., Neelov I., Rasmus K., Rodriguez Medina M., Raudsepp U., Passenko J., Söderkvist J., Sokolov A., Kuosa H., Anderson T.R., Lehmann A. & Skogen M.D. 2010: Validation of three-dimensional hydrodynamic models of the Gulf of Finland. *Boreal Env. Res*. 15: 453–479.

Orviku K., Jaagus J., Kont A., Ratas U. & Rivis R. 2003. Increasing activity of coastal processes associated with climate change in Estonia. *J. Coastal Res*. 19: 364–375.

Pettersson H. 2001. Aaltohavaintoja Suomenlahdelta. Suuntamittauksia 1990–1994. *MERI — Report Series of the Finnish Institute of Marine Research*, 44: 1–37.

Pettersson H. 2004. *Wave growth in a narrow bay*. Ph.D. thesis, Contributions no. 9, Finnish Institute of Marine Research.

Pettersson H., Kahma K.K. & Tuomi L. 2010. Predicting wave directions in a narrow bay. *J. Phys. Oceanogr*. 40: 155–169.

Pryor S.C. & Barthelmie R.J. 2003. Long-term trends in near-surface flow over the Baltic. *Int. J. Climatol*. 23: 271–289.

Pryor S.C. & Barthelmie R.J. 2010. Climate change impacts on wind energy: a review. *Renew. Sust. Energ. Rev.* 14: 430–437.

Räämet A. & Soomere T. 2010. The wave climate and its seasonal variability in the northeastern Baltic Proper. *Estonian J. Earth Sci.* 59: 100–113.

Räämet A., Suursaar Ü., Kullas T. & Soomere T. 2009. Reconsidering uncertainties of wave conditions in the coastal areas of the northern Baltic Sea. *J. Coastal Res.* Special Issue 56: 257–261.

Räämet A., Soomere T. & Zaitseva-Pärnaste I. 2010. Variations in extreme wave heights and wave directions in the north-eastern Baltic Sea. *Proc. Estonian Acad. Sci.* 59: 182–192.

Ryabchuk D., Kolesov A., Chubarenko B., Spiridonov M., Kurennoy D. & Soomere T. 2011. Coastal erosion processes in the eastern Gulf of Finland and their links with long-term geological and hydrometeorological factors. *Boreal Env. Res.* 16 (suppl. A): 117–137.

Sooäär J. & Jaagus J. 2007. Long-term variability and changes in the sea ice regime in the Baltic Sea near the Estonian coast. *Proc. Estonian Acad. Sci. Eng.* 13: 189–200.

Soomere T. 2003. Anisotropy of wind and wave regimes in the Baltic Proper. *J Sea Res.* 49: 305–316.

Soomere T. 2005. Wind wave statistics in Tallinn Bay. *Boreal Env. Res.* 10: 103–118.

Soomere T. 2008. Extremes and decadal variations of the northern Baltic Sea wave conditions. In Pelinovsky E. & Kharif Ch. (eds.), *Extreme ocean waves*, Springer Verlag, pp. 139–157.

Soomere T. & Keevallik S. 2001. Anisotropy of moderate and strong winds in the Baltic Proper. *Proc. Estonian Acad. Sci. Eng.* 7: 35–49.

Soomere T. & Zaitseva I. 2007. Estimates of wave climate in the northern Baltic Proper derived from visual wave observations at Vilsandi. *Proc Estonian Acad Sci. Eng.* 13: 48–64.

Soomere T., Myrberg K., Leppäranta M. & Nekrasov A. 2008. The progress in knowledge of physical oceanography of the Gulf of Finland: a review for 1997–2007. *Oceanologia* 50: 287–362.

Suursaar Ü. 2010. Waves, currents and sea level variations along the Letipea–Sillamäe coastal section of the southern Gulf of Finland. *Oceanologia* 52: 391–416.

Suursaar Ü. & Kullas T. 2009. Decadal variations in wave heights off Cape Kelba, Saaremaa Island, and their relationships with changes in wind climate. *Oceanologia* 51: 39–61.

Suursaar Ü., Kullas K., Otsmann M., Saaremäe I., Kuik J. & Merilain M. 2006. Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. *Boreal Env. Res.* 11: 143–159.

Suursaar Ü, Kullas T. & Szava-Kovats R. 2010. Wind and wave storms, storm surges and sea level rise along the Estonian coast of the Baltic Sea. *WIT Transactions on Ecology and the Environment* 127: 149–160.

Zaitseva-Pärnaste I., Suursaar Ü., Kullas T., Lapimaa S. & Soomere T. 2009. Seasonal and long-term variations of wave conditions in the northern Baltic Sea. *J. Coastal Res.* Special Issue 56: 277–281.